

14-513/18-613, Summer 2020
Proxy Lab: Writing a Caching Web Proxy
Assigned: Mon, Jul. 27, 2020

This lab requires submitting two versions of your code: one as an initial checkpoint, and the second as your final version. The dates and weights for your course grade are indicated in the following table:

Version	Due Date	Max. Grace Days	Weight in Course
Checkpoint	Mon, Aug. 3	1	2%
Final	Fri, Aug. 7	1	6%

1 Introduction

A *proxy server* is a computer program that acts as an intermediary between clients making requests to access resources and the servers that satisfy those requests by serving content. A *web proxy* is a special type of proxy server whose clients are typically web browsers and whose servers are web servers providing web content. When a web browser uses a proxy, it contacts the proxy instead of communicating directly with the web server; the proxy forwards the client's request to the web server, reads the server's response, then forwards the response to the client.

Proxies are useful for many purposes. Sometimes proxies are used in firewalls, so that browsers behind a firewall can only contact a server beyond the firewall via the proxy. A proxy may also perform translations on pages, for example, to make them viewable on web-enabled phones. Importantly, proxies are used as anonymizers: by stripping requests of all identifying information, a proxy can make the browser anonymous to web servers. Proxies can even be used to cache web objects by storing local copies of objects from servers and then responding to future requests by reading them out of its cache rather than by communicating again with a remote server.

This lab has three parts. An implementation of the first part will be submitted as your checkpoint. Your final submission will then incorporate the extensions forming the second and third parts. For the first part, you will create a proxy that accepts incoming connections, reads and parses requests, forwards requests to web servers, reads the servers' responses, and forwards the responses to the corresponding clients. The first part will involve learning about basic HTTP operation and how to use sockets to write programs that communicate over network connections. In the second part, you will upgrade your proxy to deal with multiple concurrent connections. This will introduce you to dealing with concurrency, a crucial systems concept. In the third and last part, you will add caching to your proxy using a simple main memory cache of recently accessed web content.

You will debug and test your program with PXYDRIVE, a testing framework we provide, as well as by accessing your proxy via standard tools, including a web browser. The grading of your code will involve both automated and manual testing. Your code will also be reviewed for correctness and for style.

2 Logistics

This is an individual project. You are allowed only one grace day for the checkpoint. There are no grace or late days for the final. **Do not request an extension.** By CMU policy, no assignments for this course can be accepted after the last day of classes. You should do your work on the Shark machines.

3 Handout instructions

3.1 Robust I/O package

The handout directory contains the files `csapp.c` and `csapp.h`, which comprise the CS:APP package discussed in the CS:APP3e textbook. The CS:APP package includes the robust I/O (RIO) package. When reading and writing socket data, you should use the RIO package instead of low-level I/O functions, such as `read`, `write`, or standard I/O functions, such as `fread`, and `fwrite`.

The CS:APP package also contains a collection of *wrapper* functions for system calls that check the return code and exit when there's an error. You will find that the set of wrapper functions provided is a subset of those from the textbook and the lecture notes. We have disabled ones for which exiting upon error is not the correct behavior for a server program. For these, you must check the return code and devise ways to handle these errors that minimize their impact.

3.2 Modularity

The skeleton file `proxy.c`, provided in the handout, contains a `main` function that does practically nothing. You should fill in that file with your proxy implementation. Modularity, though, should be an important consideration, and it is important for you to separate the individual modules of your implementation into different files. For example, **your cache should be largely (or completely) decoupled from the rest of your proxy**, so one good idea is to move the implementation of the cache into separate code and header files `cache.c` and `cache.h`.

3.3 Makefile

Since you are free to add your own source files for this lab, you are responsible for updating the Makefile. The entire project should compile without warnings, and you will want to determine the appropriate set of compilation flags (including optimization, linking, and debugging flags) for your final submission.

3.4 Other provided resources

Included with your starter code, in the `pxy` directory, is a pair of programs `PXYDRIVE` and `PXYREGRESS` (given as files `pxydrive.py` and `pxyregress.py`, respectively.) `PXYDRIVE` is a testing framework for your proxy. `PXYREGRESS` provides a way to run a series of standard tests on your proxy using `PXYDRIVE`. Both programs are documented in the `PXYDRIVE` user manual, available at:

Also included, in the `tests` directory, is a series of 51 test files to test various aspects of your proxy. Each of these is a command file for `PXYDRIVE`. You will want to learn about the operation of `PXYDRIVE` and how each of these tests operate.

Finally, you are provided with a reference implementation of a proxy, named `proxy-ref`. It is compiled to execute on a Linux machine.

4 Part I: Implementing a sequential web proxy

The first step is implementing a basic sequential proxy that handles HTTP/1.0 GET requests. Your proxy need not handle other request types, such as POST or HTTPS.

When started, your proxy should listen for incoming connections on a port whose number is specified on the command line. Once a connection is established, your proxy should read the entirety of the request from the client and parse the request. It should determine whether the client has sent a valid HTTP request; if so, it should 1) establish its own connection to the appropriate web server, 2) request the object the client specified, and 3) read the server's response and forward it to the client.

4.1 HTTP/1.0 GET requests

When an user enters a URL such as `http://www.cmu.edu/hub/index.html` into the address bar of a web browser, the browser will send an HTTP request to the proxy that begins with a line that might resemble the following:

```
GET http://www.cmu.edu/hub/index.html HTTP/1.1\r\n
```

The proxy should parse the request into at least the following fields: the hostname, `www.cmu.edu`, and the path or query and everything following it, `/hub/index.html`. That way, the proxy can determine that it should open a connection to `www.cmu.edu` and send an HTTP request of its own starting with a line of the following form:

```
GET /hub/index.html HTTP/1.0\r\n
```

As these examples show, all lines in an HTTP request end with a carriage return (`'\r'`) followed by a newline (`'\n'`). Also important is that every HTTP request must be terminated by an empty line, consisting of just the string `"\r\n"`.

Notice in the above example that the web browser's request line ends with HTTP/1.1, while the proxy's request line ends with HTTP/1.0. Modern web browsers will generate HTTP/1.1 requests, but your proxy should handle them and forward them as HTTP/1.0 requests.

4.2 Request headers

Request headers are very important elements of an HTTP request. Headers are key-value pairs provided line-by-line following the first request line of an HTTP request, with the key and value separated by the colon (':') character. Of particular importance for this lab are the `Host`, `User-Agent`, `Connection`, and `Proxy-Connection` headers. Your proxy must perform the following operations with regard to the listed HTTP request headers:

- Always send a `Host` header. This header is necessary to coax sensible responses out of many web servers, especially those that use virtual hosting. The `Host` header describes the hostname of the web server your proxy is trying to access. For example, to access `http://www.cmu.edu/hub/index.html`, your proxy would send the following header:

```
Host: www.cmu.edu\r\n
```

It is possible that the client will attach its own `Host` header to its HTTP requests. If that is the case, your proxy should use the same `Host` header as the client.

- You should always send the following `User-Agent` header:

```
User-Agent: Mozilla/5.0 (X11; Linux x86_64; rv:3.10.0)
           Gecko/20191101 Firefox/63.01\r\n
```

The header shown above on two separate lines because it does not fit as a single line, but your proxy should send the header as a single line. It is provided as a string constant in `proxy.c`.

The `User-Agent` header identifies the client (in terms of parameters such as the operating system and browser), and web servers often use the identifying information to manipulate the content they serve. Sending this particular `User-Agent` string may improve, in content and diversity, the material returned by some web servers.

- Always send the following `Connection` header:

```
Connection: close\r\n
```

- Always send the following `Proxy-Connection` header:

```
Proxy-Connection: close\r\n
```

The `Connection` and `Proxy-Connection` headers are used to specify whether a connection will be kept alive after the first request/response exchange is completed. Specifying `close` as the value of these headers alerts web servers that your proxy intends to close connections after the first request/response exchange.

With the exception of the `Host` header, your proxy should ignore the values of the request headers described above provided by the client. Instead, it should always send the headers this document specifies.

Finally, if a client sends any additional request headers as part of an HTTP request, your proxy should forward them unchanged. Forwarding other request headers is especially important when using `PXYDRIVE` to test your proxy, because it uses headers to coordinate the actions of its client and servers.

4.3 Port numbers

There are two significant classes of port numbers for this lab: HTTP request ports and your proxy's listening port.

The HTTP request port is an optional field in the URL of an HTTP request. That is, the URL may be of the form, `http://www.cmu.edu:8080/hub/index.html`, in which case your proxy should connect to the host `www.cmu.edu` on port 8080 instead of the default HTTP port, which is port 80, and it should include the port number in the `Host` header (e.g., `www.cmu.edu:8080`.) Your proxy must properly function whether or not the port number is included in the URL.

The listening port is the port on which your proxy should listen for incoming connections. Your proxy should accept a command line argument specifying the listening port number for your proxy. For example, with the following command, your proxy should listen for connections on port 12345:

```
linux> ./proxy 12345
```

The proxy must be given a port number every time it runs. When using `PXYDRIVE`, this will be done automatically, but when you run your proxy on its own, you must provide a port number. You may select any non-privileged port (greater than 1,024 and less than 32,768) as long as it is not used by other processes. Since each proxy must use a unique listening port, and many students may be working simultaneously on each machine, the script `port-for-user.pl` is provided to help you pick your own personal port number. Use it to generate a port number based on your Andrew ID:

```
linux> ./port-for-user.pl bovik
bovik: 5232
```

The port, p , returned by `port-for-user.pl` is always an even number. So if you need an additional port number, say for the Tiny server, you can safely use ports p and $p + 1$.

Note: Upon normal execution, your proxy should not print anything. However, you should consider having a verbose mode (set with `-v` on the command line) that prints useful information for debugging.

Completing Part I satisfies the requirements for the project checkpoint. See Section 7 regarding how your proxy will be evaluated for the checkpoint.

5 Part II: Dealing with multiple concurrent requests

Production web proxies usually do not process requests sequentially; they process multiple requests in parallel. This is particularly important when handling a single request can involve a lengthy delay (as it

might when contacting a remote web server). While your proxy waits for a response from the remote web server, it can work on a pending request from another client. Indeed, most web browsers reduce latency by issuing concurrent requests for the multiple URLs embedded in a single web page requested by a single client. Once you have a working sequential proxy, you should alter it to simultaneously handle multiple requests.

5.1 POSIX Threads

You will use the POSIX Threads (Pthreads) library to spawn threads that will execute in parallel to serve multiple simultaneous requests. A simple way to serve concurrent requests is to spawn a new thread to process each request. In this architecture, the main server thread simply accepts connections and spawns off independent worker threads that deal with each request to completion and terminate when they are done. Other designs are also viable: you might alternatively decide to have your proxy create a pool of worker threads from the start. You may use any architecture you wish as long as your proxy exhibits true concurrency, but spawning a new worker thread for each request is the most straightforward approach.

A new thread is spawned in Pthreads by calling `pthread_create` with a start routine as its argument. New threads are by default joinable, which means that another thread must clean up spare resources after the thread exits, similar to how an exited process must be reaped by a call to `wait`. For a server, a better approach is to *detach* each new thread, so that spare resources are automatically reaped upon thread exit. To properly detach threads, the first line of the start routine should be as follows:

```
pthread_detach(pthread_self());
```

5.2 Race conditions

While multithreading will almost certainly improve the performance of your web proxy, concurrency comes at a price: the threat of race conditions. Race conditions most often arise when there is a shared resource between multiple threads. You must find ways to avoid race conditions in your concurrent proxy. That will likely involve both minimizing shared resources and synchronizing access to shared resources. Synchronization involves the use of locks, which come in many varieties. The Pthreads library implements the locking primitives you will need, as is discussed in Section 6.2.

5.3 Thread safety

The `open_clientfd` and `open_listenfd` functions described in the CS:APP3e textbook (and included in `csapp.c`) are based on the modern and protocol-independent `getaddrinfo` function, and thus are thread safe.

6 Part III: Caching web objects

For the final part of the lab, you will add a cache to your proxy that keeps recently used Web objects in memory. Note that a software cache bears little relation to a hardware cache, such as the one you simulated

in the Cache Lab assignment. Instead, it functions as a key-value storage, saving some block of data with an associated key, such that future requests of the key will return the stored data. Typically, a software cache is implemented using standard data structures, such as linked lists, arrays, and dynamically allocated memory blocks.

The HTTP standard defines a complex model by which web servers can give instructions as to how the objects they serve should be cached and clients can specify how caches should be used on their behalf. However, your proxy will follow a much simpler approach. When your proxy receives a GET request from a client, it should treat the URL as a key. When it then receives the requested web object from the server, it should store the object in its cache with this key. Whenever another GET request arrives with the same URL, it can retrieve the contents from its cache and respond to the client directly, rather than making a new request to the server.

Since your cache serves only to boost the performance of the proxy, it need not store every object that has ever been requested. Instead, it should limit the amount of memory used by bounding the size of the maximum cached object, as well as the total memory used for the cache.

The following two parameters (given as constants in `proxy.c`) define the two constraints on your cache size:

```
#define MAX_OBJECT_SIZE (100 * 1024)
#define MAX_CACHE_SIZE (1024 * 1024)
```

The maximum object size of 100 KiB limits the maximum size of a web object that can be stored in the cache, where a “web object” consists of the complete response made by a server to a client, including any response headers. The maximum cache size of 1 MiB limits the sum of the sizes of all web objects stored in the cache. Neither the URL keys nor the data structures you use to implement the cache are included in either of these limits.

It is mandatory for you to dynamically allocate just enough space for your web objects and your keys, and that you do not assume any fixed upper bound on the number of web objects that will be stored in the cache. Allocate only the space your cache requires, and make sure you do not have any memory leaks—a server program will fail if it cannot maintain a tight bound on the total storage it requires.

One way to implement a correct cache is to declare a local array of size `MAX_OBJECT_SIZE` in the function that handles a new connection. The function can then accumulate data as it is received from the server. If the entirety of the web server’s response is read before the maximum object size is exceeded, then space for a block can be allocated (via `malloc`), the contents copied into the block via `memcpy`, and a pointer to the block can be stored as cache data.

6.1 Eviction policy

Your proxy’s cache should employ a least-recently-used (LRU) eviction policy. (It need not be strictly LRU, since requests are processed concurrently, but it should be something reasonably close.) The initial creation of an object, as well as any reuse of the object count as uses. Since web objects vary in size, it may be necessary to evict multiple smaller objects to make room for a larger one.

	Series	Count	Points each	Total
A	Basic proxy operation	12	2	24
B	Robustness and compliance	12	1	12
Total				36

Figure 1: Checkpoint Score Computation

6.2 Synchronization

Accesses to the cache must be thread safe; ensuring that cache access is free of race conditions. This requirement will likely be a challenging aspect of the lab. In general, you will get maximum performance by having the threads hold a lock for the cache for as short a time as possible.

It is acceptable to have a single, mutual exclusion lock to control access to the cache, both for scanning the cache for a matching key and for inserting an element into the cache. However, we require that a thread must release this lock before it writes a cached web object to the client socket. Otherwise, a slow, faulty, or malicious client could cause the proxy to hang up for an indefinite amount of time while the cached object is being transmitted to it.

The requirement that a thread must release its lock on the cache before transmitting an object to the client creates a potential race condition—if other requests cause the object to be evicted, another thread may attempt to free the storage while the object is still being transmitted. The best approach is to use *reference counting*, where there is an integer count associated with each object. The reference count for an object should be incremented when it is stored in the cache and decremented when it is removed. When a thread retrieves an object from the cache it increments the reference count and decrements it when it is done transmitting the object to a client. When the reference count drops to 0, the object can safely be freed. Be sure to protect all operations on a reference count with a mutual exclusion lock, or else these operations can cause synchronization errors. (Reference counting is described in the context of file descriptors in Section 10.6 of the textbook.)

Although the book describes the use of semaphores for mutual exclusion, we do not allow you to use them. Instead, you should use a mutual exclusion lock, defined in Pthreads as data type `pthread_mutex_t`, and supporting operations `pthread_mutex_lock` and `pthread_mutex_unlock`.

7 Evaluation

The grading standards for the assignment are shown in Figures 1 and 2. Grading will be via a combination of automatic testing, manual testing, and a manual review of your code. The automatic grading will be done by running `PXYREGRESS` with the same command files you are provided. There are a total of 51 files, divided into four series, labeled A–D, as described in Section 7 of the user manual.

As shown in Figure 1, your checkpoint grade will be determined solely by the results of the tests in series A and B. These can be passed by a serial proxy. There will be no style grading or manual inspection of the checkpoint code.

Series	Count	Points each	Total
A Basic proxy operation	12	2	24
B Robustness and compliance	12	1	12
C Concurrency	10	3	30
D Cache correctness	17	2	34
Subtotal			100
Real Pages tests	4	5	20
Style			20
Total			140

Figure 2: Final Score Computation

As shown in Figure 2, your final submission will be evaluated using all four series. Series C tests can only be passed by a proxy that supports concurrent requests. Series D can only be passed by a proxy that supports caching. The first five of these can be passed by a serial proxy (with caching). The remaining ones require a concurrent proxy.

The manual *Real Pages* tests evaluate the ability of your proxy to render the following web pages. (If you read this document using a properly configured browser, you can exercise your proxy by directly clicking the following links.)

- <http://www.andrew.cmu.edu/course/18-613/>
- <http://csapp.cs.cmu.edu>
- <http://www.andrew.cmu.edu/course/18-613/proxylab/scs.html>
- <https://www.andrew.cmu.edu/course/18-613/proxylab/ece.html>

Grading with the Real Pages tests, described below, will only be performed for your code if you have passed *all* of the tests in series A, and at least 50% of the tests in *each* of series B–D. Finally, there are a total of 20 style points, also described below.

7.1 Autograding with PXYREGRESS

The PXYDRIVE testing framework is included in the handout in the subdirectories `pxy` (code) and `tests` (command files).

A typical invocation of PXYDRIVE from your code directory would be:

```
linux> pxy/pxydrive.py -p ./proxy -f tests/A01-single-fetch.cmd
```

With this invocation, the proxy will operate *internally*, under the control of PXYDRIVE. Alternatively, the proxy can be set up and run *externally*:

```
linux> ./proxy 15213 &
linux> pxy/pxydrive.py -P localhost:15213 -f tests/A01-single-fetch.cmd
```

(Normally, these two lines would be executed in separate terminal windows.) Running the proxy externally makes it possible to use programs such as GDB and VALGRIND to help with debugging. See Section 7 of the user manual for more detailed instructions.

The checkpoint runs the tests in the A and B series. You can perform this test with the command:

```
linux> pxy/pxyregress.py -p ./proxy -s AB
```

The final testing will be done with a more comprehensive set of concurrency checks, inserting random delays to exercise possible races, checking for thread-unsafe functions, checking that no write to a socket occurs while a thread is holding a lock, and checking for semaphores. You can perform this test with the command

```
linux> pxy/pxyregress.py -p ./proxy -c 4
```

For your convenience, the driver Autolab will use to test your submission is included as the file `driver.sh`. For testing the checkpoint submission, it can be invoked as:

```
linux> ./driver.sh check
```

For testing the final submission, it can be invoked as:

```
linux> ./driver.sh
```

7.2 Manual testing: Real Pages

The Real Pages tests evaluate the ability of your proxy to operate correctly when used by a web browser to render web pages. You will not have access to this testing framework, but you can try the pages yourself using a web browser.

The Real Pages testing is done using WebKit, a browser engine used in Safari and similar to Chrome, set up to connect via your proxy to the URLs listed above. While testing, Javascript will be disabled. For each page, we will reload each URL (clearing the browser's cache after each reload) at least 3 times to test your proxy's caching ability. Each load should take no longer than 10 secs. After each load, we will compare your result with the website as it is rendered without using a proxy; if they match, you will receive credit for that trial.

If your proxy exits before we finish testing, we will NOT restart it. Your proxy will only receive credit for the pages it successfully renders. We will not evaluate your proxy under any other conditions, or on any other pages.

7.3 Style Grading

The style points include a combination of points for code correctness and for coding style. Your TAs will examine your code for any correctness issues that weren't detected by the earlier tests. In particular, we

will be looking for errors such as race conditions, thread safety issues, non-LRU cache implementations, improper error handling, and memory and file descriptor leaks.

Style points will be awarded based on the usual criteria. Proper error handling is as important as ever, and modularity is of particular importance for this lab, as there will be a significant amount of code. You should also strive for portability.

8 Real-World Testing

You should also test your proxy operating using real web browsers and servers in preparation for the Real Pages tests. We do not provide the testing framework for Real Pages. Instead, you must set up and run these tests using standard tools, including those described here.

8.1 Tiny web server

Your handout directory includes the source code for the CS:APP Tiny web server. While not a full-functioning server, the server supports the operations required for this assignment. You can modify the code as you see fit.

The tiny server is a good reference for your proxy implementation because it deals with HTTP requests. Keep in mind, however, that it is not a proxy, and so its features do not exactly match those you will need in your program. Remember especially that your proxy doesn't serve its own content; it simply relays content from the server to the client.

8.2 curl

You can use `curl` to generate HTTP requests to any server, including your own proxy. It is an extremely useful debugging tool. For example, if your proxy and Tiny are both running on the local machine, Tiny is listening on port 15213, and proxy is listening on port 15214, then you can request a page from Tiny via your proxy using the following `curl` command:

```
linux> curl -v --proxy http://localhost:15214 http://localhost:15213/home.html
```

8.3 Web browsers

Eventually you should test your proxy using the *most recent version* of Mozilla Firefox. Visiting selection About Firefox in the Firefox menu will automatically update your browser to the most recent version.

To configure Firefox to work with a proxy, visit Preferences>Network Proxy>Settings in the Firefox menu and set the manual proxy configuration with your host name of the specific Shark machine you are using and with the port number for your proxy.

It will be very exciting to see your proxy working through a real Web browser. Although the functionality of your proxy will be limited, you will notice that you are able to browse many websites through your proxy.

An important caveat is that you must be very careful when testing caching using a Web browser. All modern Web browsers have caches of their own, which you should disable before attempting to test your proxy's cache.

9 Handin instructions

The provided Makefile includes functionality to build your final handin file. Issue the following command from your working directory:

```
linux> make handin
```

The output is the file `../proxylab-handin.tar`. Simply upload it to Autolab. Autolab will use your Makefile to rebuild your proxy from scratch, and it will then run tests using `PXYREGRESS`.

10 Resources

- Chapters 10–12 of the textbook contains useful information on system-level I/O, network programming, HTTP protocols, and concurrent programming.
- RFC 1945 (<http://www.ietf.org/rfc/rfc1945.txt>) is the complete specification for the HTTP/1.0 protocol. The specification is large and complex. You only need to implement the portions of the protocol we describe in this document.

11 Advice

- It is important to adopt the proper mindset when writing a server program. Think carefully about how long-running processes should react to different types of errors, including network failures and malformed data. Your server should do its best to continue in the face of errors. For example, it's OK to fail to respond to a malformed request from a client, but this should not cause your program to terminate. Robustness implies a higher level of code quality, as well, avoiding defects such as segmentation faults, memory leaks, and file descriptor leaks.
- Your proxy will have to do something about SIGPIPE signals. The kernel will sometimes deliver a SIGPIPE to a process when a socket gets disconnected. Although the default action for a process that receives SIGPIPE is to terminate, your proxy should not terminate due to that signal. (To generate the SIGPIPE signal in Firefox, press F5 twice in quick succession to reload the page.)
- Sometimes, calling `read` to receive bytes from a socket that has been prematurely closed will cause `read` to return `-1` with `errno` set to `ECONNRESET`. The same result can occur when calling `write` to send bytes on a socket that has been prematurely closed. Your proxy should not terminate due to these errors.

- Remember that not all content on the web is ASCII text. Much of the content on the web is binary data, such as images and video. Ensure that you account for binary data when selecting and using functions for network I/O. In particular, you should never use string functions (e.g., `strlen` and `strcpy`) on web data, since these will terminate prematurely when they encounter a byte with value 0, which can occur at any position in a binary file. (The preferred way to copy data is to use `memcpy`.)
- You *can* assume that the request and header lines will be ASCII text, and you can assume that there is some reasonable upper bound on their line lengths.
- Similarly, it is inefficient to use line-oriented I/O routines, such as `rio_readlineb`, on binary data. These routines will break the data into chunks according to the placement of newline characters (hex value 0x0A). With binary data, these can appear in arbitrary positions in a file. Instead, use functions, such as `rio_readn` and `rio_readnb`, that operate independently of the data values.
- Forward all requests as HTTP/1.0 even if the original request was HTTP/1.1.
- Firefox (like all modern web browsers) has useful debugging tools you may take advantage of. The network tab allows you to view the status of network requests, which is useful for determining if your threads terminate and if all requests are fulfilled.
- There are several ways you can track the LRU state of the cached objects. One way is to keep a counter that is incremented for each request, storing the value of the counter each time a cached object is accessed. Another way is to store the cache as a list and move an object to the head of the list each time it is referenced. It's up to you to select an implementation. Just make sure to use synchronization primitives to avoid race conditions on the counters, the lists, and other shared data structures.
- Avoid an overly complex design. If your synchronization code is too complex for you to easily comprehend, it almost certainly has bugs! Your first version should be the simplest one that satisfies the functional requirements. Then you can refine it to improve efficiency. A correct, but slow program is far preferable to a fast, buggy one.